FINAL TECHNICAL REPORT
"STATISTICAL INFERENCE FOR CHANGE-OF-APERTURE PROBLEMS IN COMMAND AND CONTROL"

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Objectives

Almost every aspect of Command and Control (C2) deals with making decisions in the presence of uncertainty. The uncertainty may come from noisy data or, indeed, regions of the battlespace where there are no data at all. Statistical models that account for noisy data are well accepted by the science and engineering community, but the full quantification of uncertainty due to lack of knowledge (caused either by hidden processes or missing data) is a challenging statistical-modeling problem. When the hidden process is a random map, the problem is even more challenging.

A map is a powerful way of summarizing spatial data and information, and our view is that from great maps come knowledgable command decisions. Different commanders have different "apertures" and hence the maps should depict information consistently, regardless of scale. The battle commander needs more global, aggregated information, whereas the platoon commander is often making decisions based on local, more focused information. Our emphasis is on making maps that are statistically optimal and are easily interpretable at different resolutions/apertures.

Approach

We took two approaches. The first approach combines the two aspects of noisy or missing data and change-of-aperture, to construct statistical models that deal directly with computation of posterior statistical distributions of the map. Because of the hierarchical nature of C2 problems involving change-of-aperture, models can often be built using an acyclic directed graph (ADG). In an ADG, each 'node' can have 'parents' that it depends on, and the node can have 'children' that depend on it. If each node in an ADG has only one parent, then the ADG is a tree. Spatial dependence can be incorporated through the ADG's parent-child relationship, which is a type of multi-resolution model. In the case of a tree-structured model, very fast statistical algorithms can be developed for removing noise and filling in missing data at all apertures. The resulting posterior distributions are summarized in different ways, depending on the command queries.

In the second approach, we developed statistical methodology to produce an (approximately) optimal map for all queries. Most queries are nonlinear in nature, but the most frequently used optimality for map estimation is geared toward answering linear questions. The approach we take is to produce a single map estimate that preserves certain first- and second-order moment properties of the underlying model, making it approximately optimal for answering nonlinear questions. One particular map we concentrated on was the danger field.

Finally, the temporal component has been incorporated to allow fast updating of spatial maps based on newly acquired C2 data. As a result, the maps can be animated and their evolution studied during the course of a battle.

Results

The research focused on the mapping of the danger field and like quantities in the battlespace. A hierarchical framework, along with an object-oriented computer program, has been developed to describe the spatio-temporal evolution, and interaction, of battlespace constituents (Cressie et al., 2002). The program simulates noisy data coming from different sources and at different spatial and temporal resolutions. The data are used to map the danger potential of the enemy at any location in the battlespace. The resulting map can then be used to answer diverse queries at different levels in the chain of command. Due to the diversity of the queries, care needs to be taken in obtaining a statistically optimal map. The approach taken in Aldworth and Cressie (2002), covariance-matching kriging (CM), is intuitively appealing and computationally fast. Cressie and Johannesson (2001) give a practical implementation of the CM method in spatial settings. Also, a paper is in preparation giving a fully Bayesian approach to estimating the danger-potential fields using sequential imputation.

To deal with consistency of predictions across changes of aperture, we developed fast prediction algorithms for multiscale graphical models in spatial and temporal settings. Huang et al. (2002) extend the recursive Kalman-filter-prediction algorithm to the class of multiscale tree-structured models. A paper giving an extension of these spatial tree models to spatio-temporal tree models is in preparation. Shen et al. (2002) use a multiresolution wavelet basis to detect changes in maps from one time point to another. With regard to statistical theory, Huang and Cressie (2000) and Cressie et al. (2000) investigate limiting properties of Markov models on directed graphs, which are called partially ordered Markov models (POMMs). Cressie and Liu (2001) investigate the equivalence of certain binary POMMs and symmetric Markov random fields, and they give conditions for their equivalence. In the case of equivalence, the binary POMM allows fast simulation of the symmetric Markov random field.

Research has continued in exploring the nature of spatial (and temporal) hierarchical models. Cressie and Mugglin (2000) and Mugglin et al. (2002) take a Bayesian approach in developing spatio-temporal models for infectious-disease count data. These models estimate how an epidemic spreads, spatially and temporally, given aggregated small-area count data, using the methodology of Markov chain Monte Carlo. Hrafnkelsson and Cressie (2003) also take a Bayesian approach for the modeling of spatial count data, with application to nuclear fall-out data. In modeling the underlying Gaussian mean process (linked to the count data), they compare Markov random fields and geostatistical models, and show that the computationally faster Markov random fields give very similar results to the non-Gaussian geostatistical models. Stern and Cressie (2001) investigate Bayesian model diagnostics for spatial lattice data, an important part of any development of spatial statistical models. Kaiser et al. (2002) develop inference for a class of spatial mixture models that use exponential-family conditional distributions to model the underlying latent spatial process.

Impact/Applications

We have developed two web sites at The Ohio State University:
www.stat.ohio-state.edu/~C2
considers probability and statistics in Command and Control.
www.stat.ohio-state.edu/~sses/research_onr.html
considers all research conducted with the support of the Office of Naval Research.

Personnel

Principal Investigator:	Noel Cressie, Ph.D.
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Publications

Aldworth, J. and Cressie, N. (2002). Prediction of nonlinear spatial functionals. *Journal of Statistical Planning and Inference*, forthcoming.

Cressie, N. and Collins, L. (2001). Patterns in spatial point locations: Local indicators of spatial association in a minefield with clutter. *Naval Research Logistics*, **38**, 333-347.

Cressie, N. and Johannesson, G. (2000). Kriging for cut-offs and other difficult problems, in *geoEnv III – Geostatistics for Environmental Applications*, eds. P. Monestiez et al., Kluwer, Dordrecht, 299-310.

Cressie, N. and Lawson, A. B. (2000). Hierarchical probability models and Bayesian analysis of mine locations. *Advances in Applied Probability*, **32**, 315-330.

Cressie, N. and Liu, C. (2001). Binary Markov mesh models and symmetric Markov random fields: Some results on their equivalence, in *Methodology and Computing in Applied Probability*, **3**, 5-34.

Cressie, N. and Mugglin, A.S. (2000). Spatio-temporal hierarchical modeling of an infectious disease from (simulated) count data, in *Compstat. Proceedings in Computational Statistics*, eds. J. G. Bethlehem and P. Van der Heijden. Physica-Verlag, Heidelberg, 41-52.

Cressie, N., Wendt, D., Johannesson, G., Mugglin, A., and Hrafnkelsson, B. (2002). A spatial-temporal statistical approach to problems in command and control, in *Proceedings of Sixth U. S. Army Conference on Applied Statistics*, ed. B. Bodt, forthcoming.

Cressie, N., Zhu, J., Baddeley, A. J., and Nair, M. G. (2000). Directed Markov point processes as limits of partially ordered Markov models. *Methodology and Computing in Applied Probability*, **2**, 5-21.

Hrafnkelsson, B. and Cressie, N. (2003). Hierarchical modeling of count data with application to nuclear fall-out. *Journal of Environmental and Ecological Statistics*, forthcoming.

Huang, H.-C. and Cressie, N. (2000). Asymptotic properties of maximum (composite) likelihood estimators for partially ordered Markov models. *Statistica Sinica*, **10**, 1325-1344.

Huang, H.-C. and Cressie, N. (2000). Deterministic/stochastic wavelet decomposition for recovery of signal from noisy data. *Technometrics*, **42**, 262-276.

Huang, H.-C. and Cressie, N. (2001). Multiscale graphical modeling in space: Applications to command and control, *in Spatial Statistics: Methodological Aspects and Applications*, ed. M. Moore. Springer Lecture Notes in Statistics No. **159**, Springer, NY, 83-113.

Huang, H.-C., Cressie, N., and Gabrosek, J. (2002). Fast, resolution-consistent spatial prediction of global processes from satellite data. *Journal of Computational and Graphical Statistics*, **11**, 63-88.

Kaiser, M. S., Cressie, N., and Lee, J. (2002). Spatial mixture models based on exponential family conditional distributions. *Statistica Sinica*, **12**, 449-474.

Mugglin, A. S., Cressie, N., and Gemmell, I. (2002). Hierarchical statistical modeling of influenza-epidemic dynamics in space and time. *Statistics in Medicine*, **21**, forthcoming.

Shen, X., Huang, H.-C., and Cressie, N. (2002). Nonparametric hypothesis testing for a spatial signal. *Journal of the American Statistical Association*, forthcoming.

Stern, H. S. and Cressie, N. (2001). Posterior predictive model checks for disease mapping models. *Statistics in Medicine*, **19**, 2377-2397.

Zhu, J., Lahiri, S. N., and Cressie, N. (2001). Asymptotic distribution of the empirical cumulative distribution function predictor under nonstationarity, in *Spatial Statistics: Methodological Aspects and Applications*, ed. M. Moore. Springer Lecture Notes in Statistics, No. **159**, Springer, NY, 1-20.

Conference participation directly related to C2 research

8/99 Organizer of session, "Spatial Methodology for Minefield Detection", at the Joint Statistical Meetings, Baltimore, MD. (The session showcased ONR supported research in minefield detection and included 4 papers and remarks from the session chair.)

10/00 Presented an invited paper at Sixth Army Conference on Applied Statistics, Houston, TX; "A spatial-temporal statistical approach to problems in command and control"

1/01 Invited seminar speaker in the Interdisciplinary Research Seminar on Statistical Signal and Image Processing, Departments of Electrical Engineering and Statistics, The Ohio State University, Columbus, OH. "A spatial-temporal statistical approach to problems in command and control"

7/01 Presented an invited paper at RSS2001, Royal Statistical Society Annual Meeting, Glasgow, Scotland; "Multiresolution statistical mapping from spatio-temporal data"

10/01 Invited seminar speaker, Centre de Recherdes Mathematiques, University of Montreal, Canada; "Nonparametric hypothesis testing for a spatial signal"; and "Spatial-temporal prediction at multiple resolutions"

12/01 Presented an invited paper (with X. Shen and H.-C. Huang) at 11^{th} International Workshop on Stereology, Stochastic Geometry, and Related Fields, University of Western Australia, Perth, Western Australia; "Nonparametric hypothesis testing for a spatial signal"

3/02 Invited seminar speaker, Department of Statistics, Case Western Reserve University, Cleveland, OH; "Nonparametric hypothesis testing for a spatial signal"

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14. ABSTRACT
A map is a powerful way of summarizing spatial data; in the arena of Command and Control (C2), great maps can produce knowledgable command decisions. Two approaches to statistically optimal mapping are taken. The first develops spatial multiresolution Kalman filtering of data at various apertures, and the second develops constrained optimal spatial prediction to answer nonlinear C2 questions consistently. Finally, the temporal component is introduced to allow updating of current maps based on newly acquired C2 data.

15. SUBJECT TERMS
C2; constrained kriging; danger field; multiresolution Kalman filter; spatio-temporal statistics

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